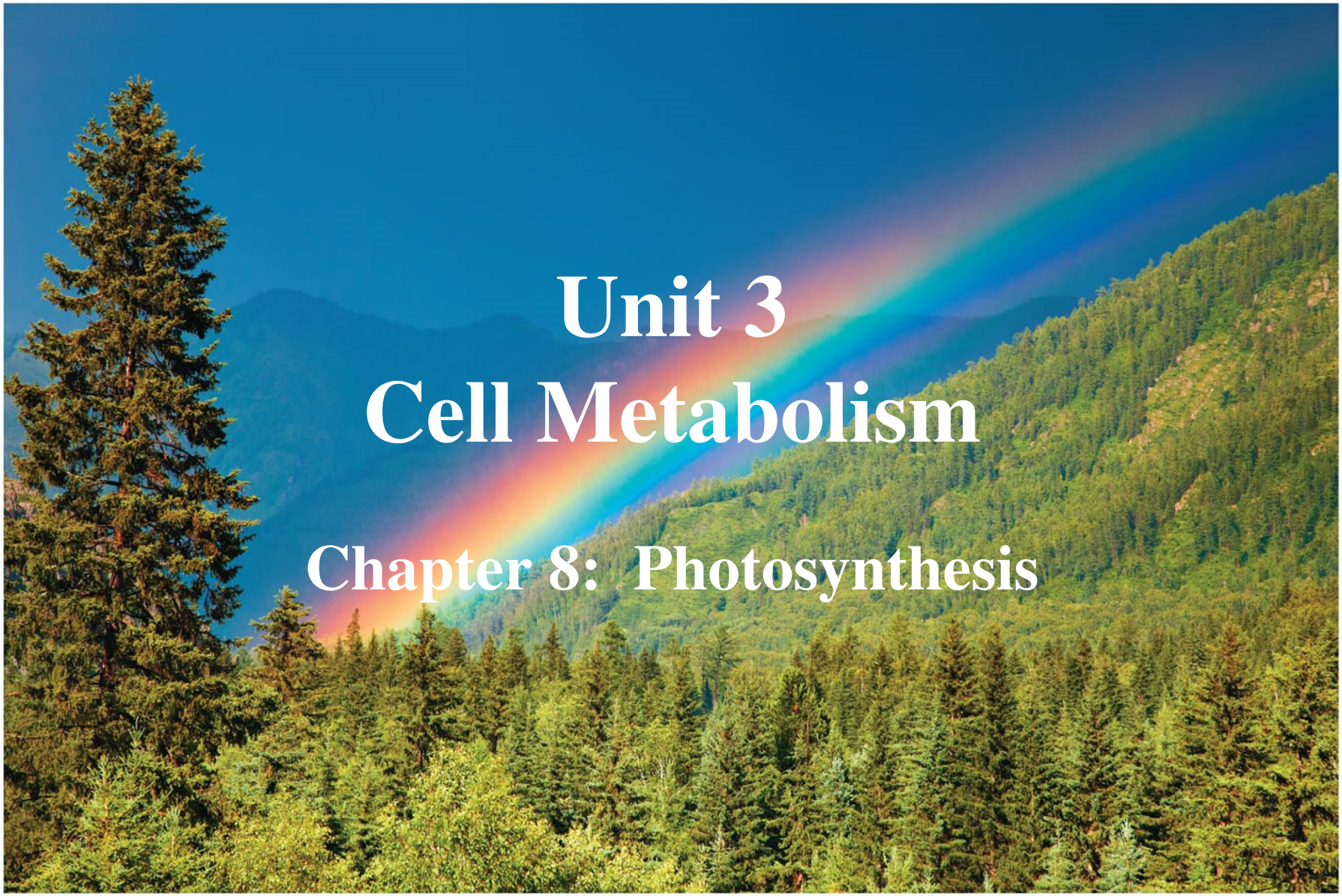


Unit 3
Cell Metabolism

Chapter 8: Photosynthesis

Overview: The Process That Feeds the Biosphere

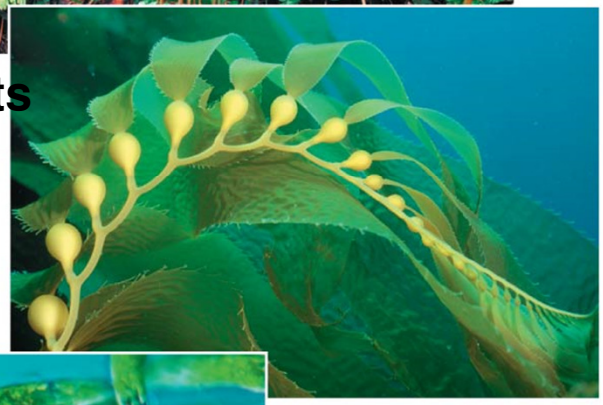
- **Photosynthesis** is the process that converts solar energy into chemical energy
  - Directly or indirectly, photosynthesis nourishes almost the entire living world
- **Autotrophs** sustain themselves without eating anything derived from other organisms
  - "Self-feeders"
  - Produce organic molecules from CO_2 and other inorganic molecules (aka-*producers*!)
- Almost all plants are *photoautotrophs*
  - Use energy of sunlight to make organic molecules

- **Heterotrophs** obtain their organic material from other organisms
  - *Consumers*
- *Decomposers* feed on remains of dead organisms

- Almost all heterotrophs, including humans, depend on photoautotrophs for food and O_2

- Photosynthesis occurs in plants, algae, certain other protists, and some prokaryotes

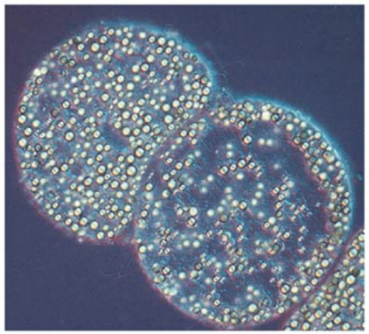
(a) Plants



(b) Multicellular alga

(c) Unicellular eukaryotes

(d) Cyanobacteria



(e) Purple sulfur bacteria

Concept 8.1: Photosynthesis converts light energy to the chemical energy of food

- The structural organization of photosynthetic cells includes enzymes and other molecules grouped together in a membrane
- This organization allows for the chemical reactions of photosynthesis to proceed efficiently
- Chloroplasts are structurally similar to and likely evolved from photosynthetic bacteria
  - Endosymbiont theory

Chloroplasts: The Sites of Photosynthesis in Plants

- Leaves are the major locations of photosynthesis
- Their green color is from **chlorophyll**, the green pigment within chloroplasts
- Chloroplasts are found mainly in cells of the **mesophyll**, the interior tissue of the leaf
- CO_2 enters and O_2 exits the leaf through microscopic pores called **stomata**
- Water and sugar are transported through veins
- The chlorophyll is in the membranes of **thylakoids** (connected sacs in the chloroplast)
  - Thylakoids may be stacked in columns called *grana*
- Chloroplasts also contain **stroma**, a dense interior fluid

Figure 8.3a

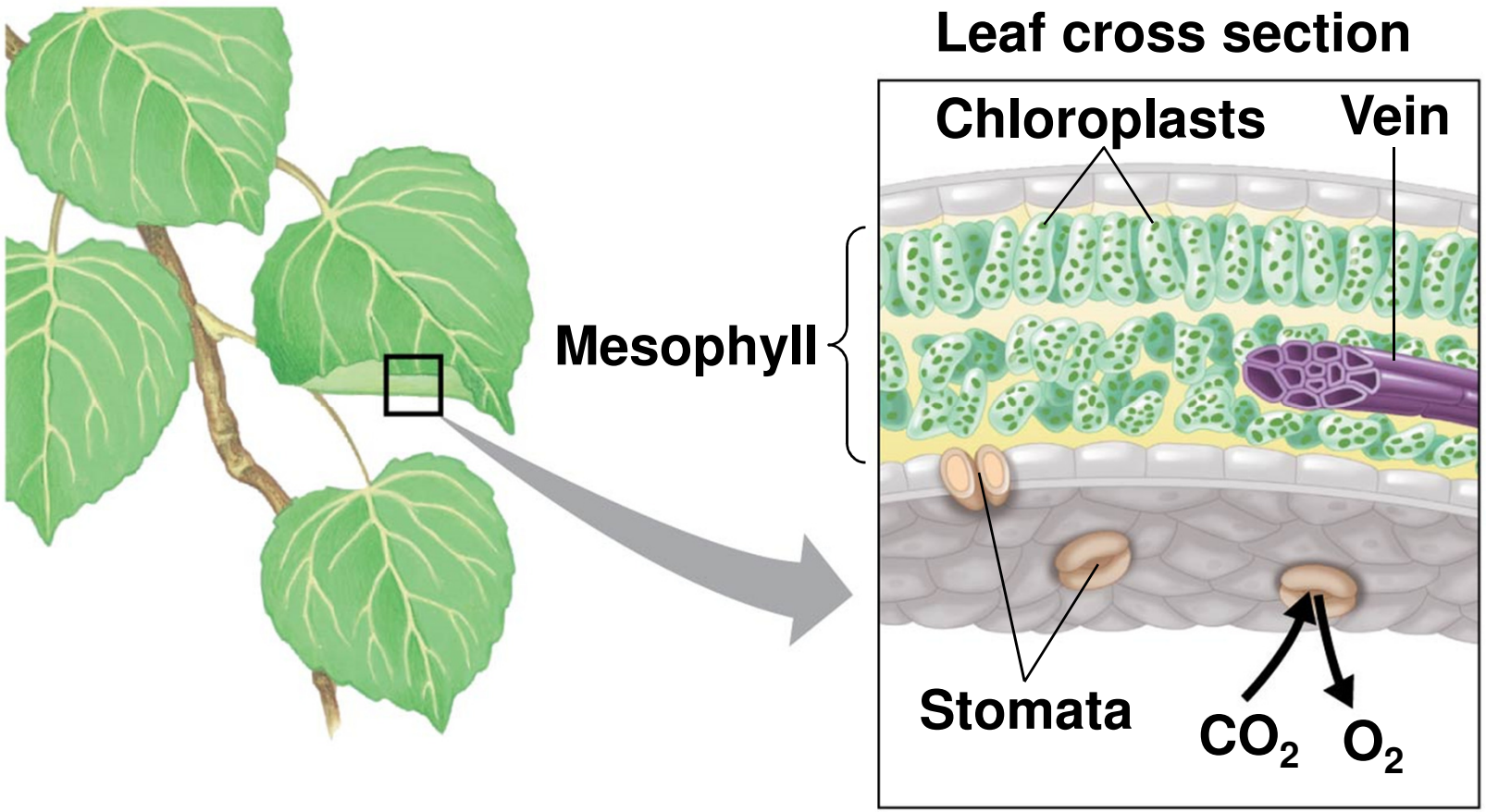
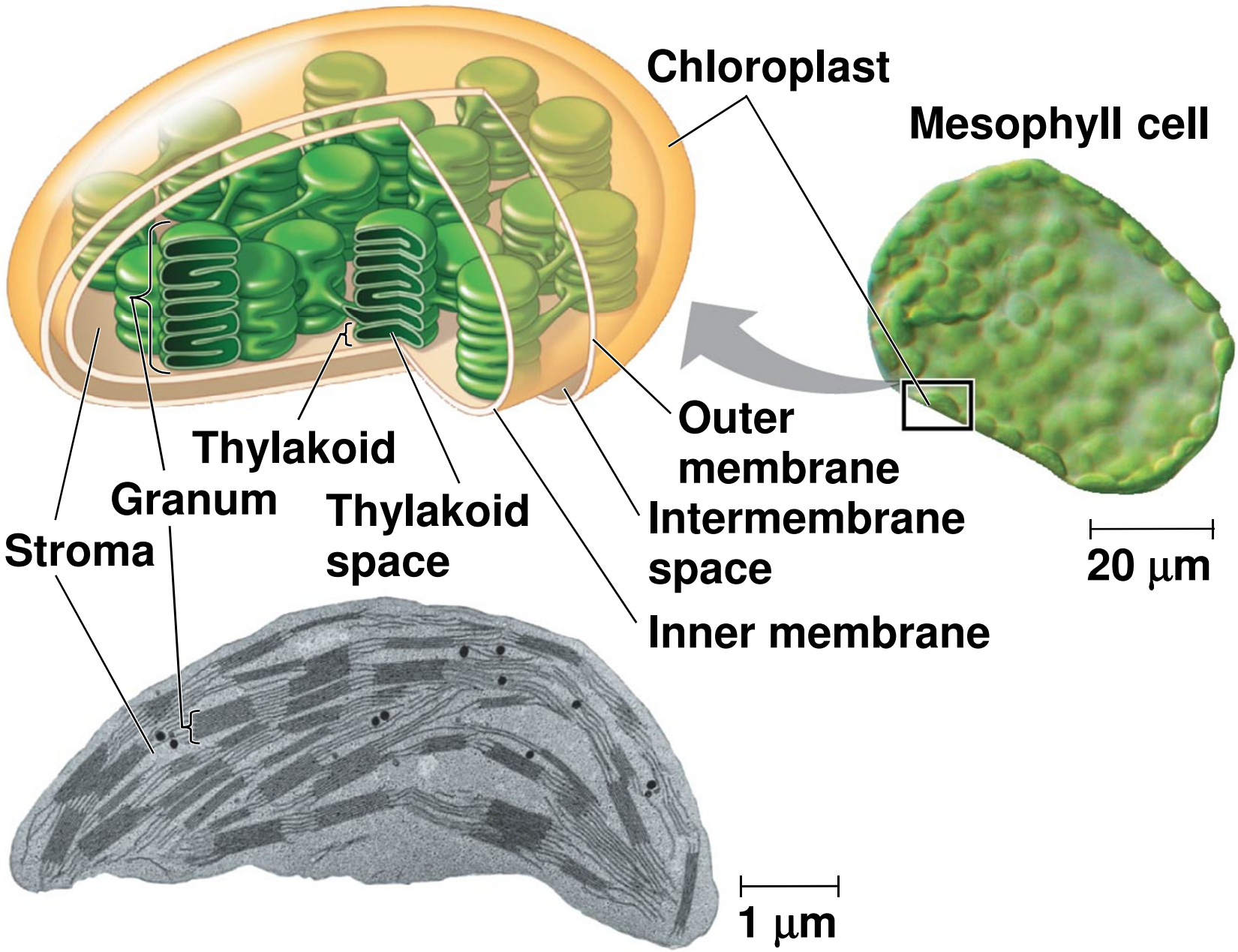

Leaf cross section
Chloroplasts
Vein
Mesophyll
Stomata
CO_2
O_2

Figure 8.3b


Chloroplast
Mesophyll cell
Outer membrane
Intermembrane space
Inner membrane
Thylakoid
Granum
Thylakoid space
Stroma
20 μm
1 μm

Tracking Atoms Through Photosynthesis: *Scientific Inquiry*

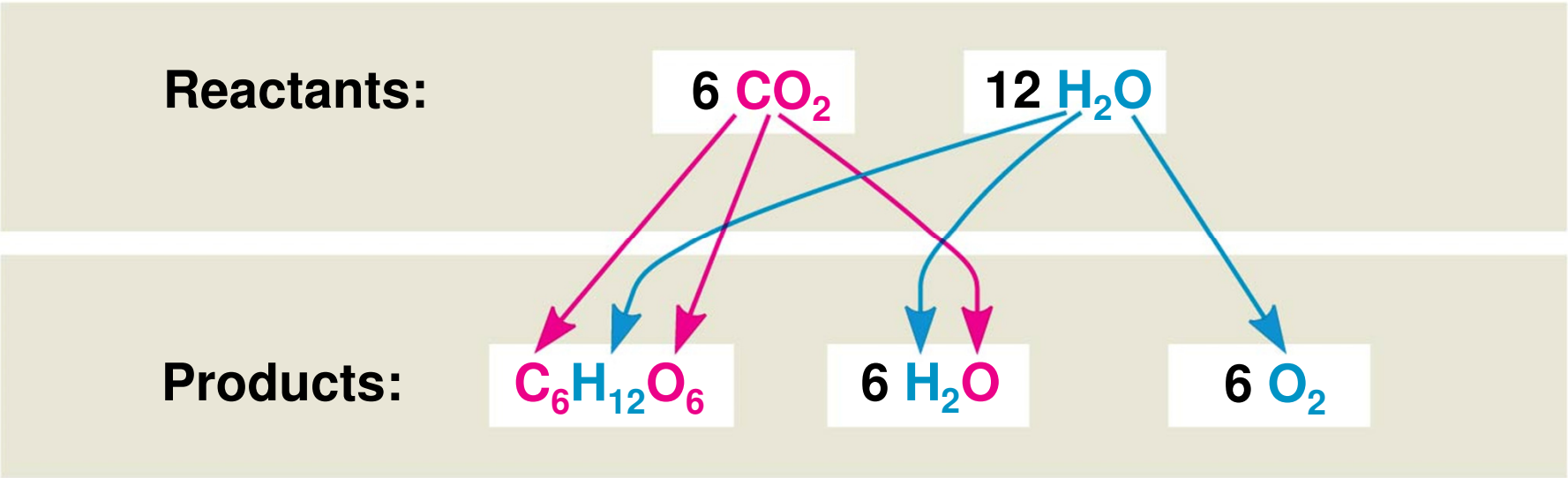
- Photosynthesis is a complex series of reactions that can be summarized as the following equation

$$6\ CO_2 + 12\ H_2O + \text{Light energy} \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

- Overall chemical change during photosynthesis is the reverse of that during cellular respiration

The Splitting of Water

- Chloroplasts split H_2O into hydrogen and oxygen
  - Incorporates the electrons of hydrogen into sugar molecules
  - Releases oxygen as a by-product



Photosynthesis as a Redox Process

- Photosynthesis reverses the direction of electron flow compared to respiration
- Photosynthesis is a redox process in which
  - H_2O is oxidized
  - CO_2 is reduced to sugar
- Photosynthesis is an <u>endergonic</u> process
  - Requires input of energy
    - Provided by light

becomes reduced

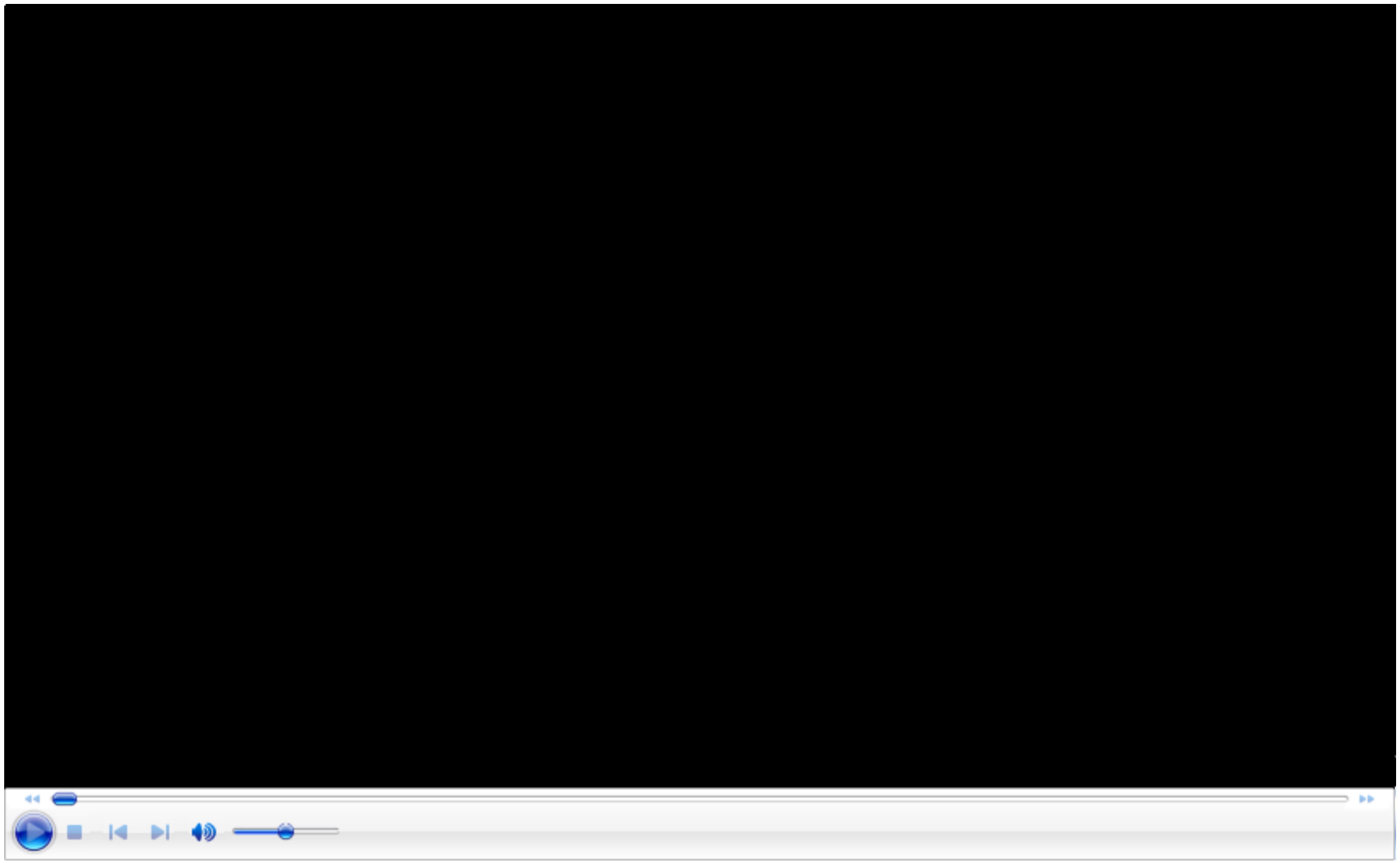
$$\text{Energy} + 6\,CO_2 + 6\,H_2O \longrightarrow C_6H_{12}O_6 + 6\,O_2$$

becomes oxidized

The Two Stages of Photosynthesis: *A Preview*

- Photosynthesis consists of two stages:
  - **Light reactions** (the *photo* part)
  - **Calvin cycle** (the *synthesis* part)
- The light reactions (in the thylakoids)
  - Split H_2O
    - Provides source of electrons and protons (H^+)
  - Release O_2 as byproduct
  - Reduce the electron acceptor, **$NADP^+$**, to NADPH
  - Generate ATP from ADP by adding a phosphate group, **photophosphorylation**

- The Calvin cycle (in the stroma)
  - Forms sugar from CO_2, using ATP and NADPH
  - Begins with **carbon fixation**
    - Incorporating CO_2 into organic molecules
  - Sometimes called light-independent reactions
    - Does not need light DIRECTLY
    - But relies on ATP produced from light reactions



Video: Photosynthesis

Figure 8.5-1

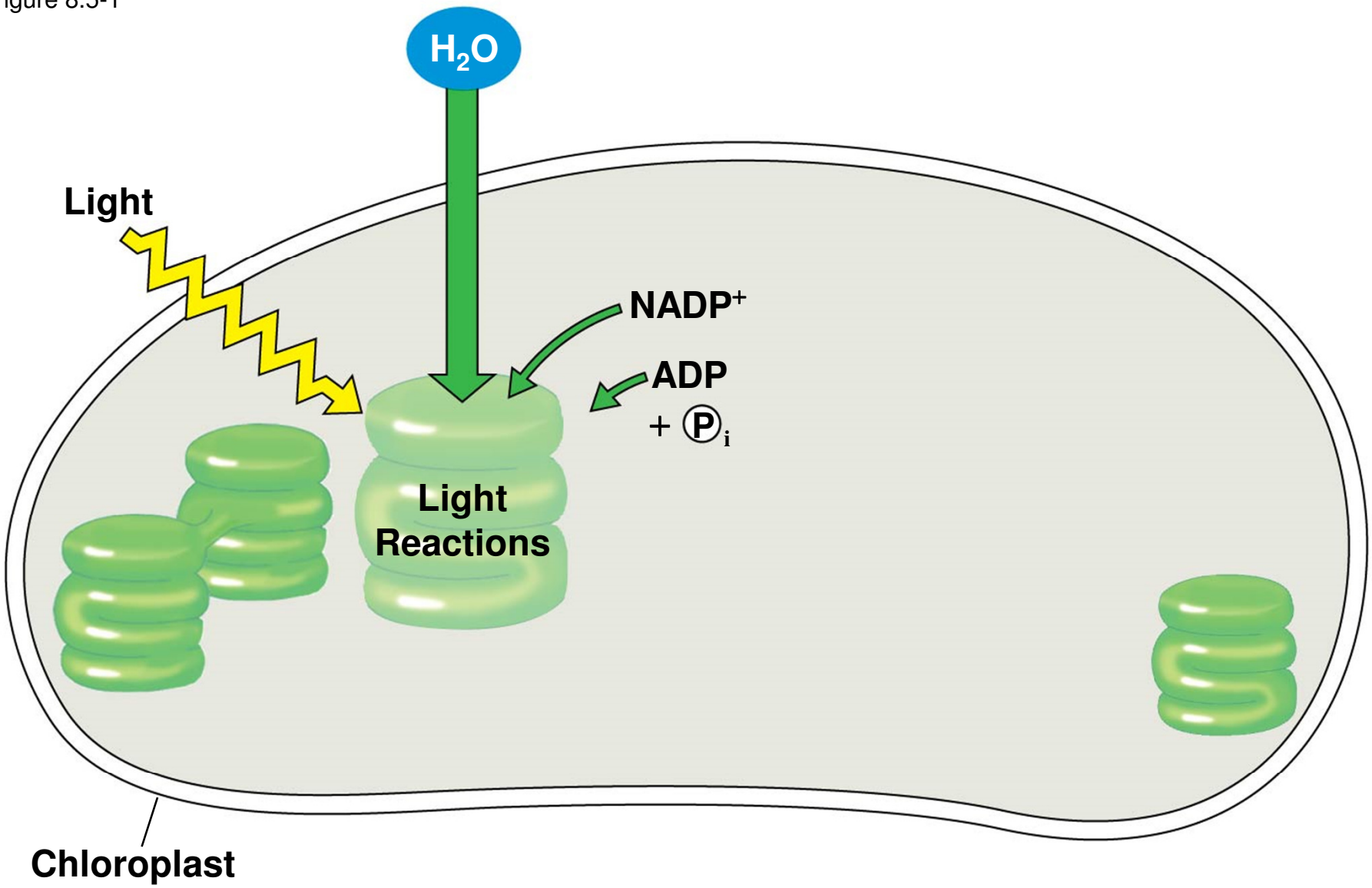


Figure 8.5-2

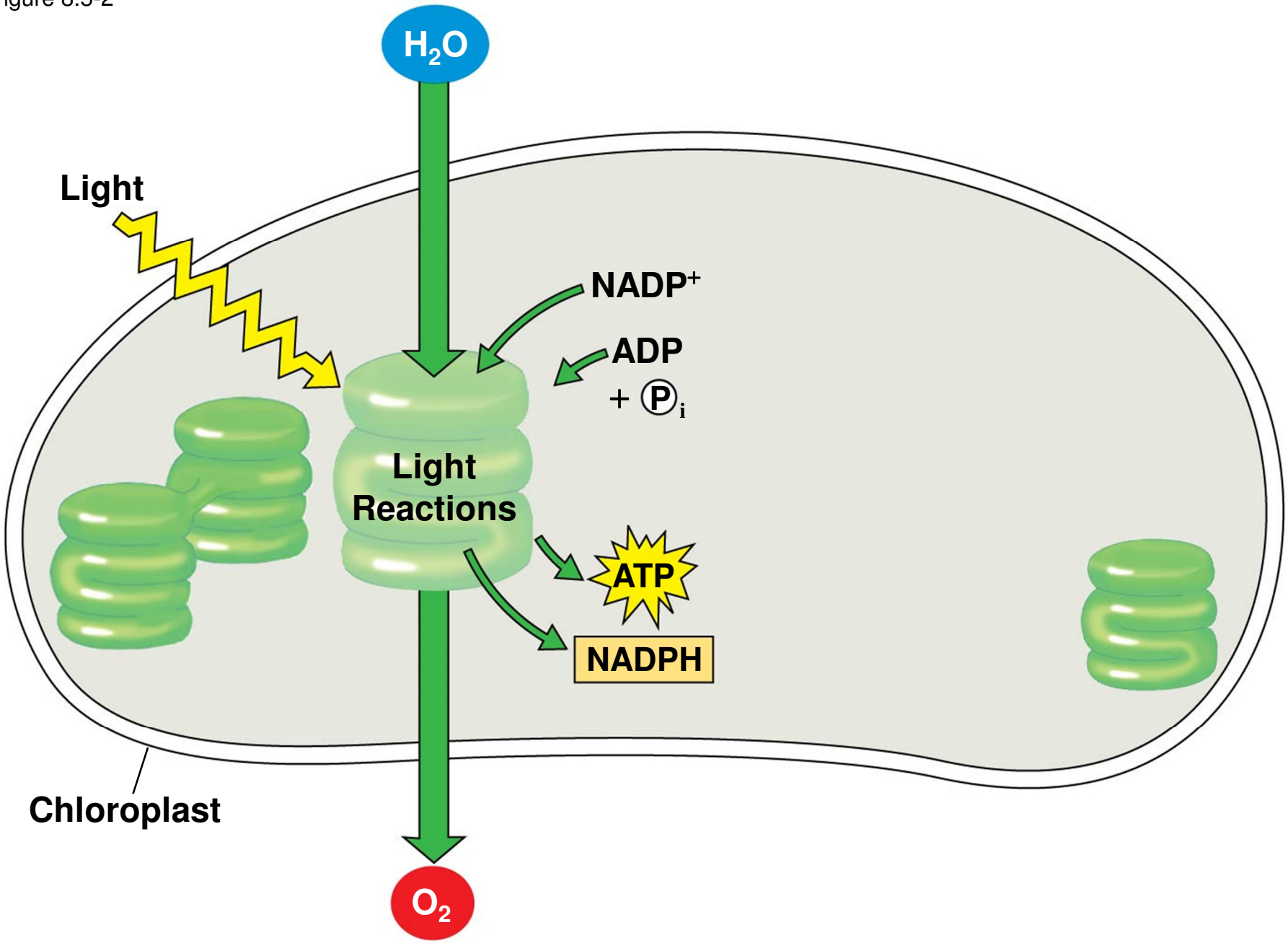

H_2O
Light
$NADP^+$
ADP
+ P_i
Light
Reactions
ATP
NADPH
Chloroplast
O_2

Figure 8.5-3

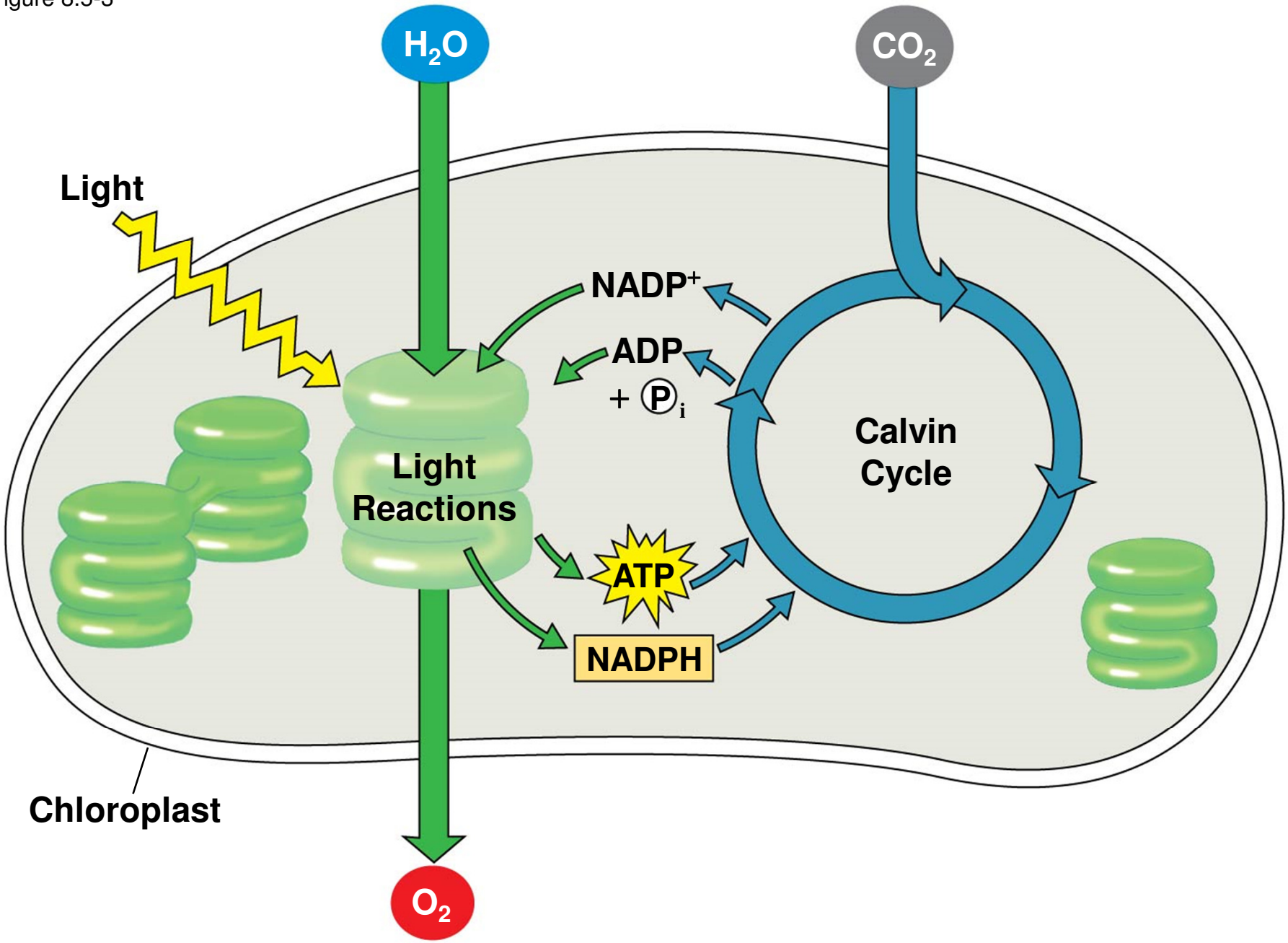
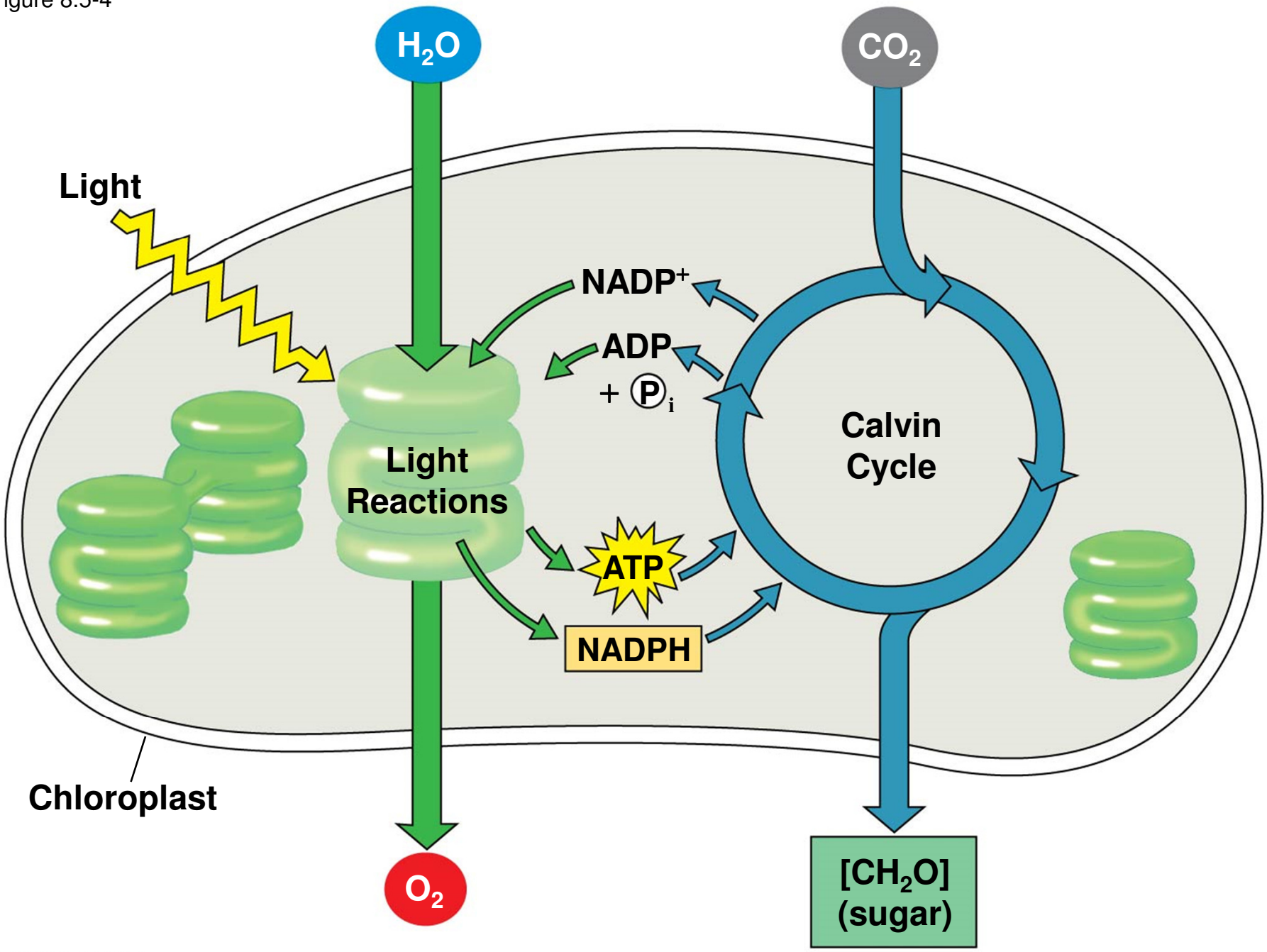

H_2O
CO_2
Light
$NADP^+$
ADP
+ P_i
Calvin
Cycle
Light
Reactions
ATP
NADPH
Chloroplast
O_2

Figure 8.5-4


H_2O
CO_2
Light
$NADP^+$
ADP
+ P_i
Light
Reactions
Calvin
Cycle
ATP
NADPH
Chloroplast
O_2
$[CH_2O]$
(sugar)

Concept 8.2: The light reactions convert solar energy to the chemical energy of ATP and NADPH

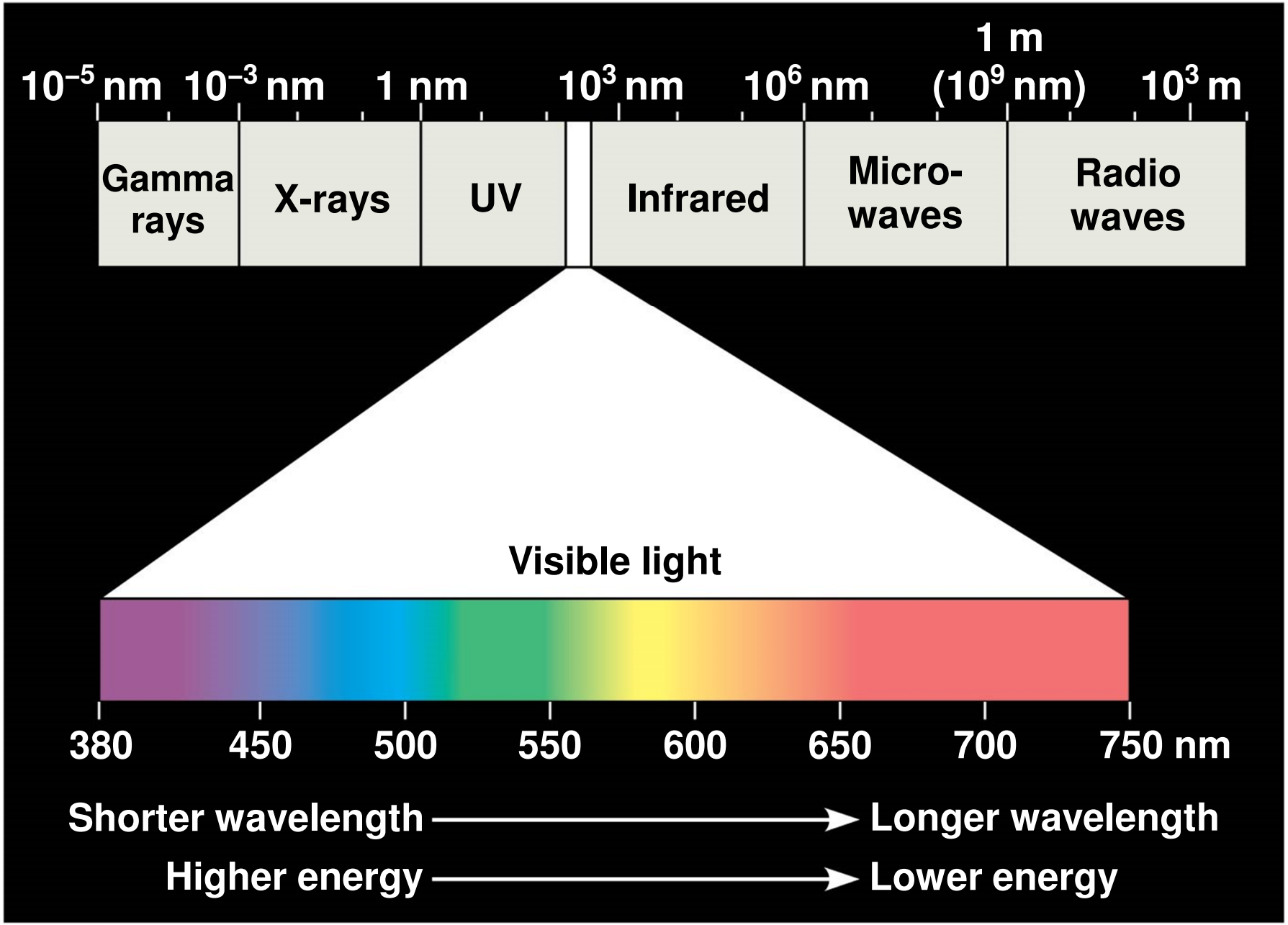
- Chloroplasts are solar-powered chemical factories
- Their thylakoids transform light energy into the chemical energy of ATP and NADPH

The Nature of Sunlight

- Light is a form of electromagnetic energy, also called electromagnetic radiation
- Like other electromagnetic energy, light travels in rhythmic waves
- **Wavelength** is the distance between crests of waves
- Wavelength determines the type of electromagnetic energy

- The **electromagnetic spectrum** is the entire range of electromagnetic energy, or radiation
- **Visible light** consists of wavelengths (including those that drive photosynthesis) that produce colors we can see
- Light also behaves as though it consists of discrete particles, called **photons**
- The amount of energy is inversely related to the wavelength of light
  - The shorter the wavelength, the greater the energy of each photon

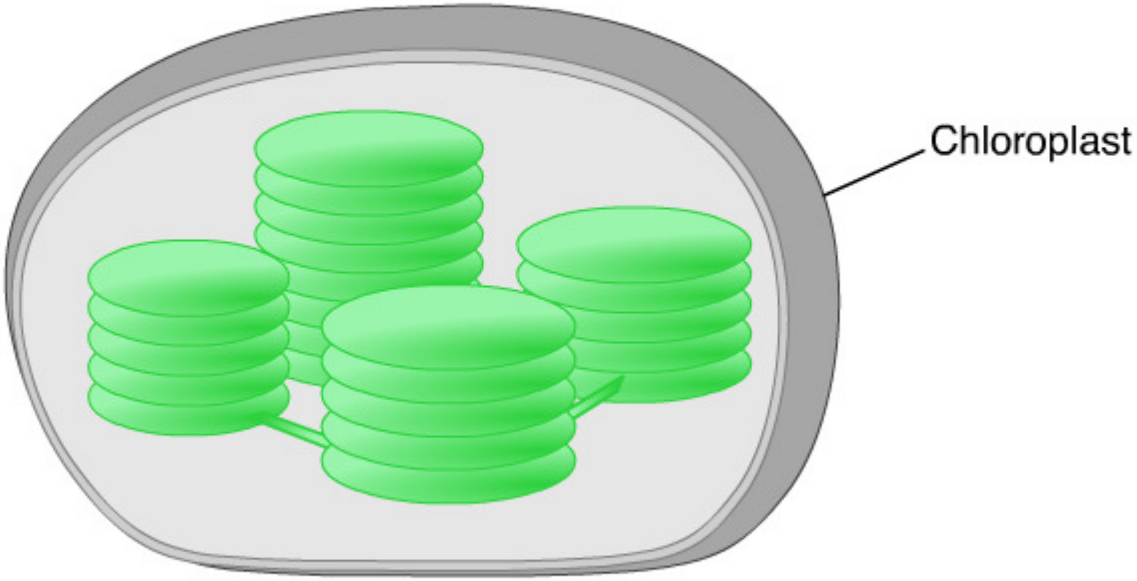
Figure 8.6


10^{-5} nm
10^{-3} nm
1 nm
10^{3} nm
10^{6} nm
1 m
(10^{9} nm)
10^{3} m
Gamma rays
X-rays
UV
Infrared
Micro-waves
Radio waves
Visible light
380
450
500
550
600
650
700
750 nm
Shorter wavelength
Longer wavelength
Higher energy
Lower energy

Photosynthetic Pigments: The Light Receptors

- *Pigments* are substances that absorb visible light
- Different pigments absorb different wavelengths
- Wavelengths that are not absorbed are reflected or transmitted
- Leaves appear green because chlorophyll
  - Absorbs violet-blue and red light
  - Reflects and transmits green light

Light

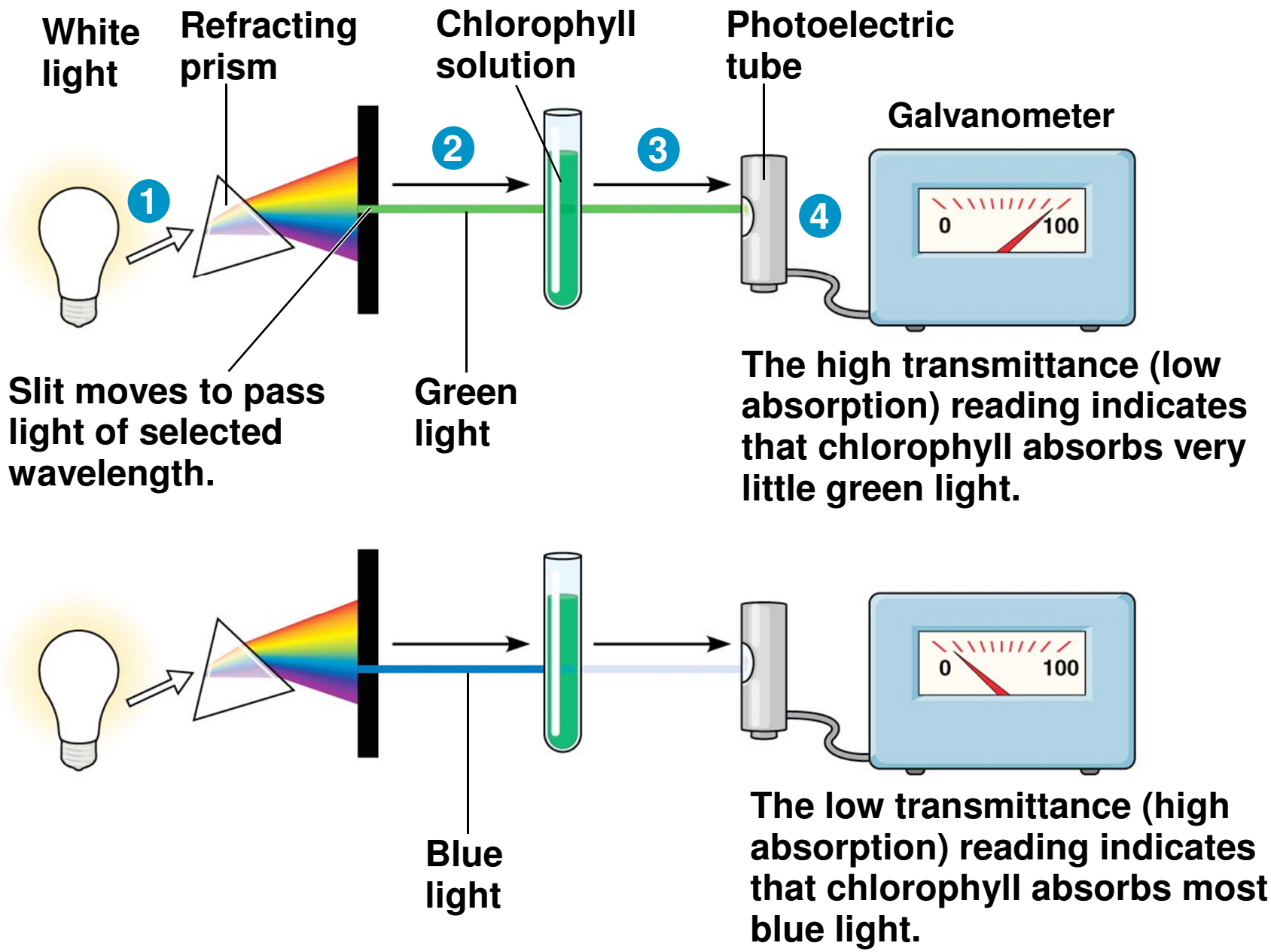


Animation: Light and Pigments
Right click slide / Select play

- A **spectrophotometer** measures a pigment's ability to absorb various wavelengths
  - This machine sends light through pigments and measures the fraction of light transmitted at each wavelength

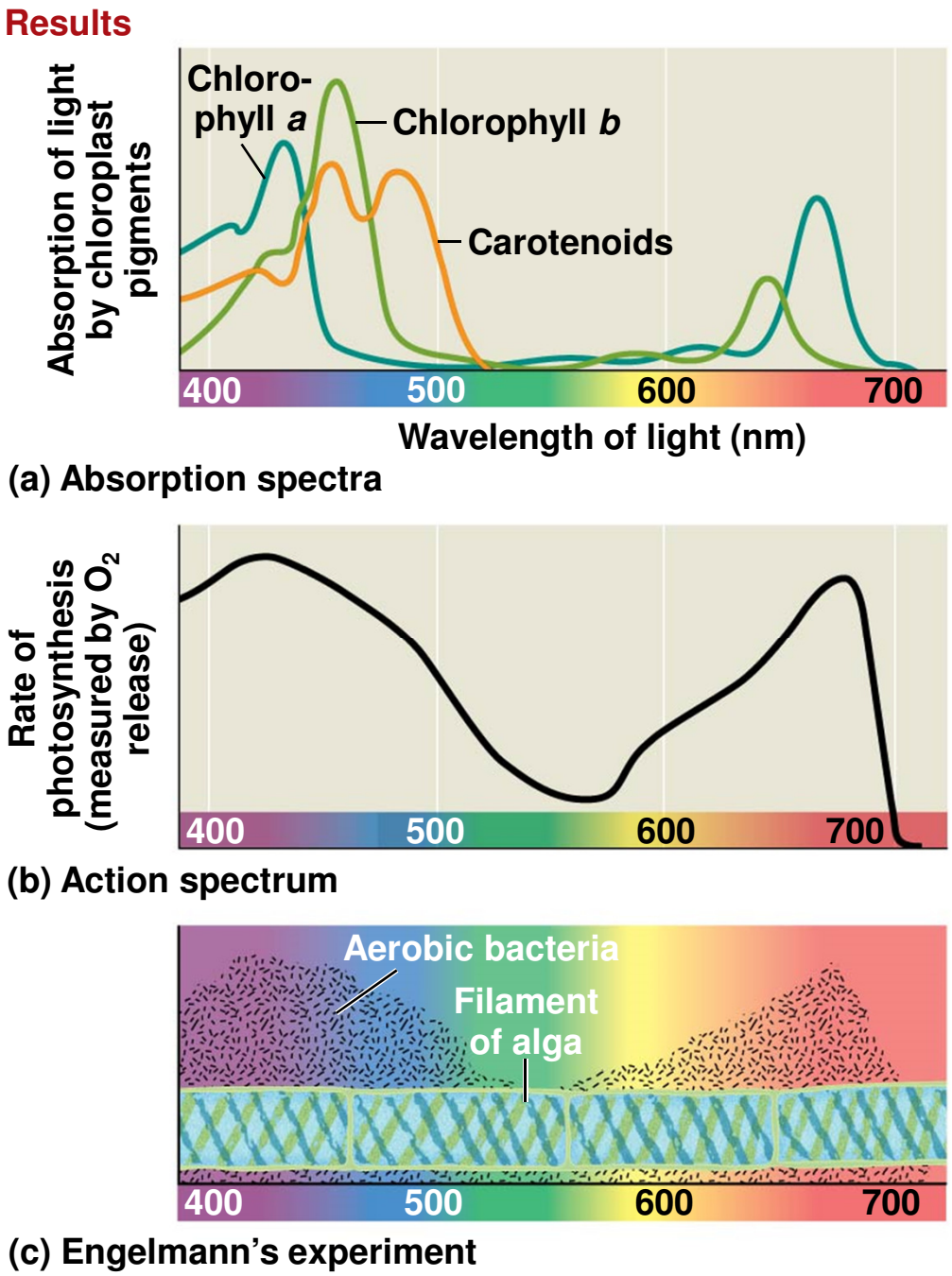
Figure 8.8

Technique



- An **absorption spectrum** is a graph plotting a pigment's light absorption versus wavelength
- The absorption spectrum of **chlorophyll *a*** suggests that violet-blue and red light work best for photosynthesis
- Accessory pigments include **chlorophyll *b*** and a group of pigments called *carotenoids*
- An **action spectrum** profiles the relative effectiveness of different wavelengths of radiation in driving a process

Figure 8.9

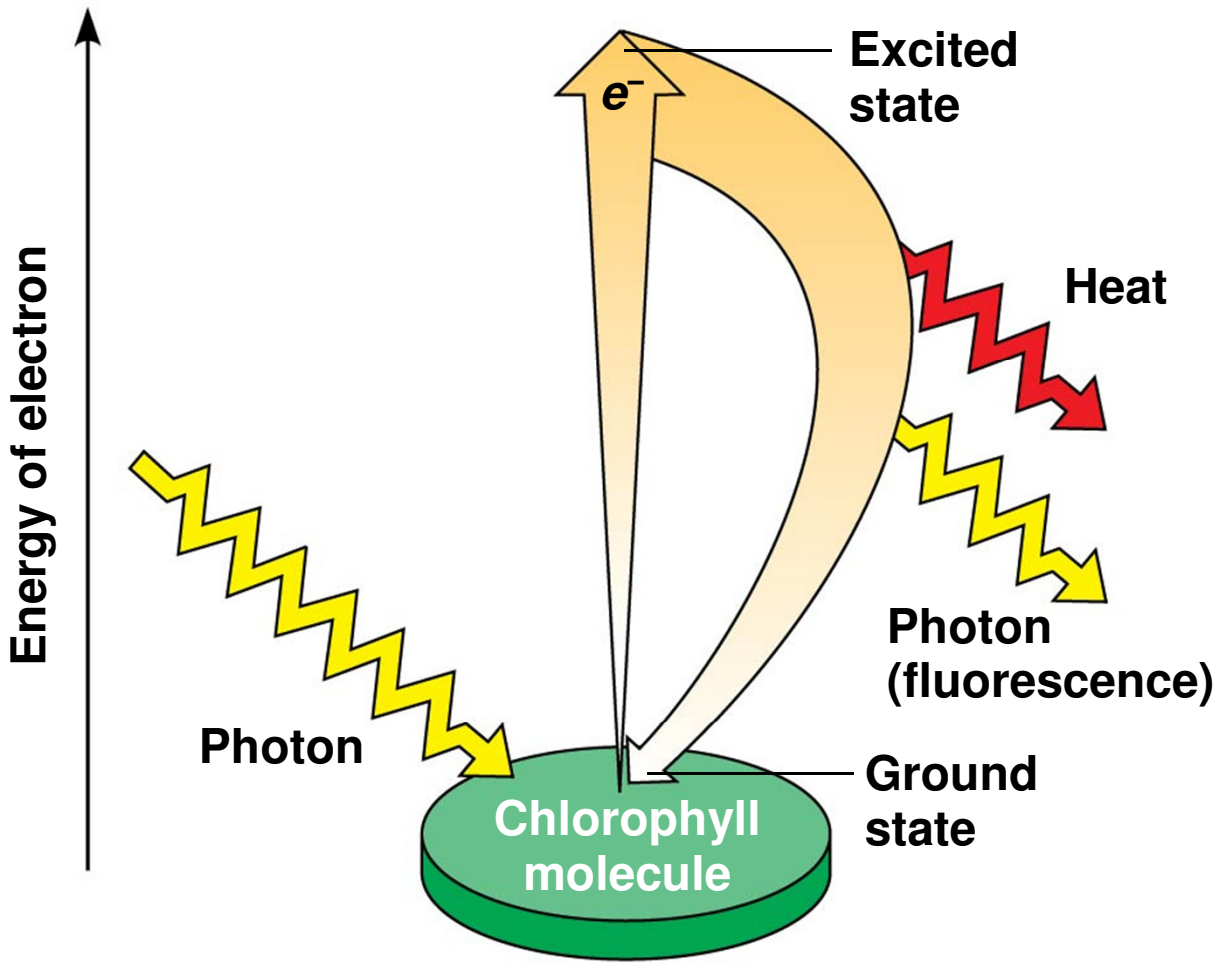

Results
Absorption of light by chloroplast pigments
Chloro-phyll a
Chlorophyll b
Carotenoids
400
500
600
700
Wavelength of light (nm)
(a) Absorption spectra
Rate of photosynthesis (measured by O_2 release)
400
500
600
700
(b) Action spectrum
Aerobic bacteria
Filament of alga
400
500
600
700
(c) Engelmann's experiment

- Chlorophyll *a* is the main photosynthetic pigment
- Accessory pigments, such as chlorophyll *b* and **carotenoids**, broaden the spectrum used for photosynthesis
  - Carotenoids are various shades of yellow and orange
  - Offer *photoprotection* by absorbing excessive light that would damage chlorophyll

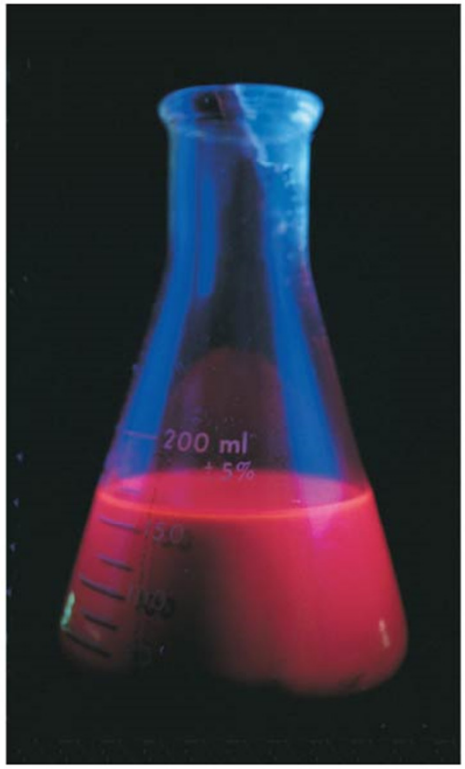
Excitation of Chlorophyll by Light

- When a pigment absorbs light, it goes from a ground state to an excited state,
  - Excited state is unstable
- When excited electrons fall back to the ground state, photons are given off
  - This afterglow is called fluorescence
- If illuminated, an isolated solution of chlorophyll will fluoresce, giving off light and heat
  - Appears green under visible light

Figure 8.11



(a) Excitation of isolated chlorophyll molecule

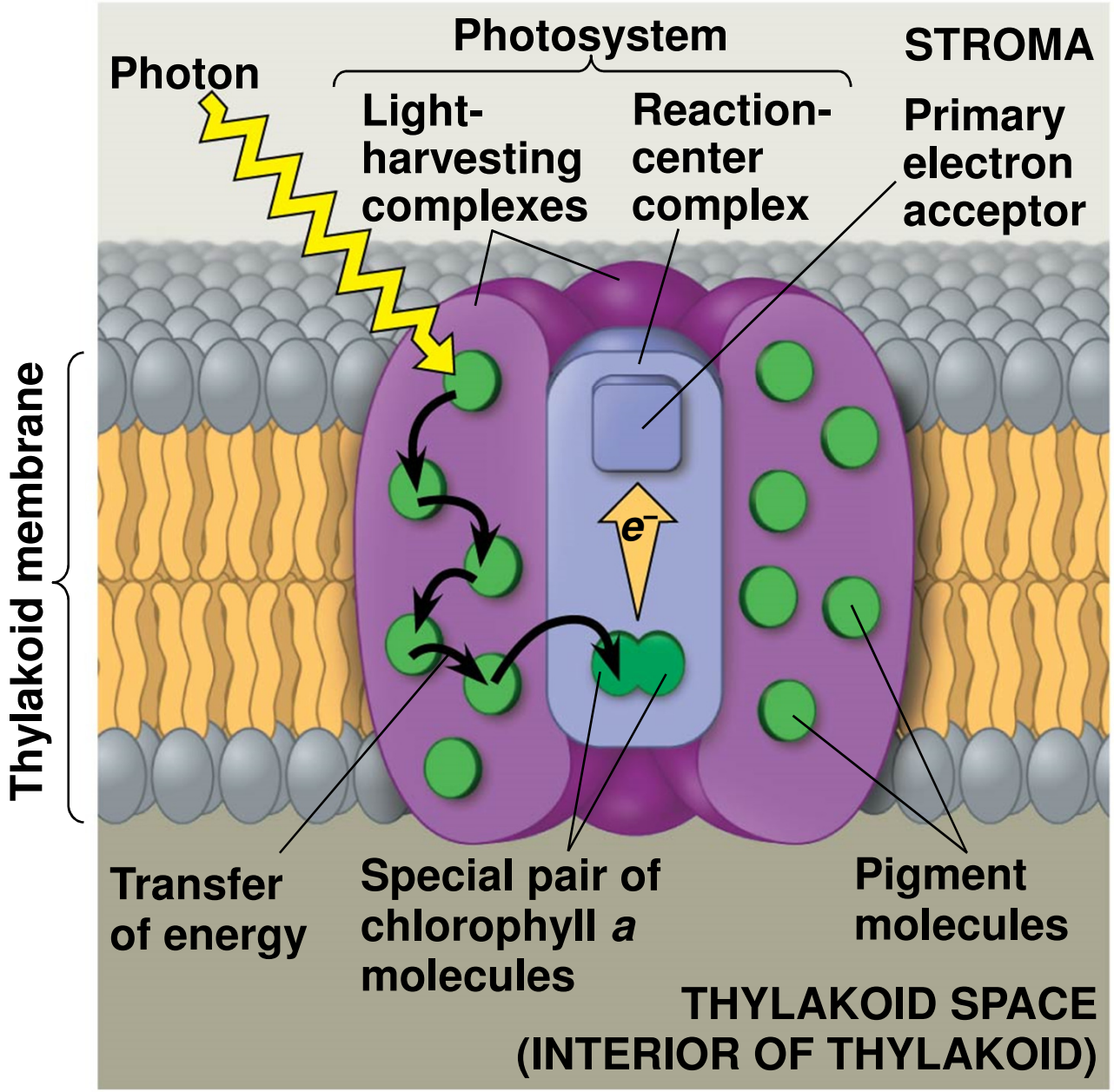


(b) Fluorescence

A Photosystem: A Reaction-Center Complex Associated with Light-Harvesting Complexes

- A **photosystem** consists of a **reaction-center complex** (a type of protein complex) surrounded by light-harvesting complexes
- The **light-harvesting complexes** (pigment molecules bound to proteins) transfer the energy of photons to the reaction center
  - Act as antenna for reaction-center complex

Figure 8.12a



(a) How a photosystem harvests light

- A **primary electron acceptor** in the reaction center accepts excited electrons and is reduced as a result
- Solar-powered transfer of an electron from a chlorophyll *a* molecule to the primary electron acceptor is the first step of the light reactions

- There are two types of photosystems in the thylakoid membrane
  - Function as a UNIT
- **Photosystem II (PS II)** functions first (the numbers reflect order of discovery) and is best at absorbing a wavelength of 680 nm
  - The reaction-center chlorophyll *a* of PS II is called P680
- **Photosystem I (PS I)** is best at absorbing a wavelength of 700 nm
  - The reaction-center chlorophyll *a* of PS I is called P700

Linear Electron Flow

- **Linear electron flow** involves the flow of electrons through both photosystems to produce ATP and NADPH using light energy

- Light reactions use solar power to generate ATP and NADPH
  - Provides chemical energy and reducing power so Calvin cycle can synthesize carbohydrates

Figure 8.13-5

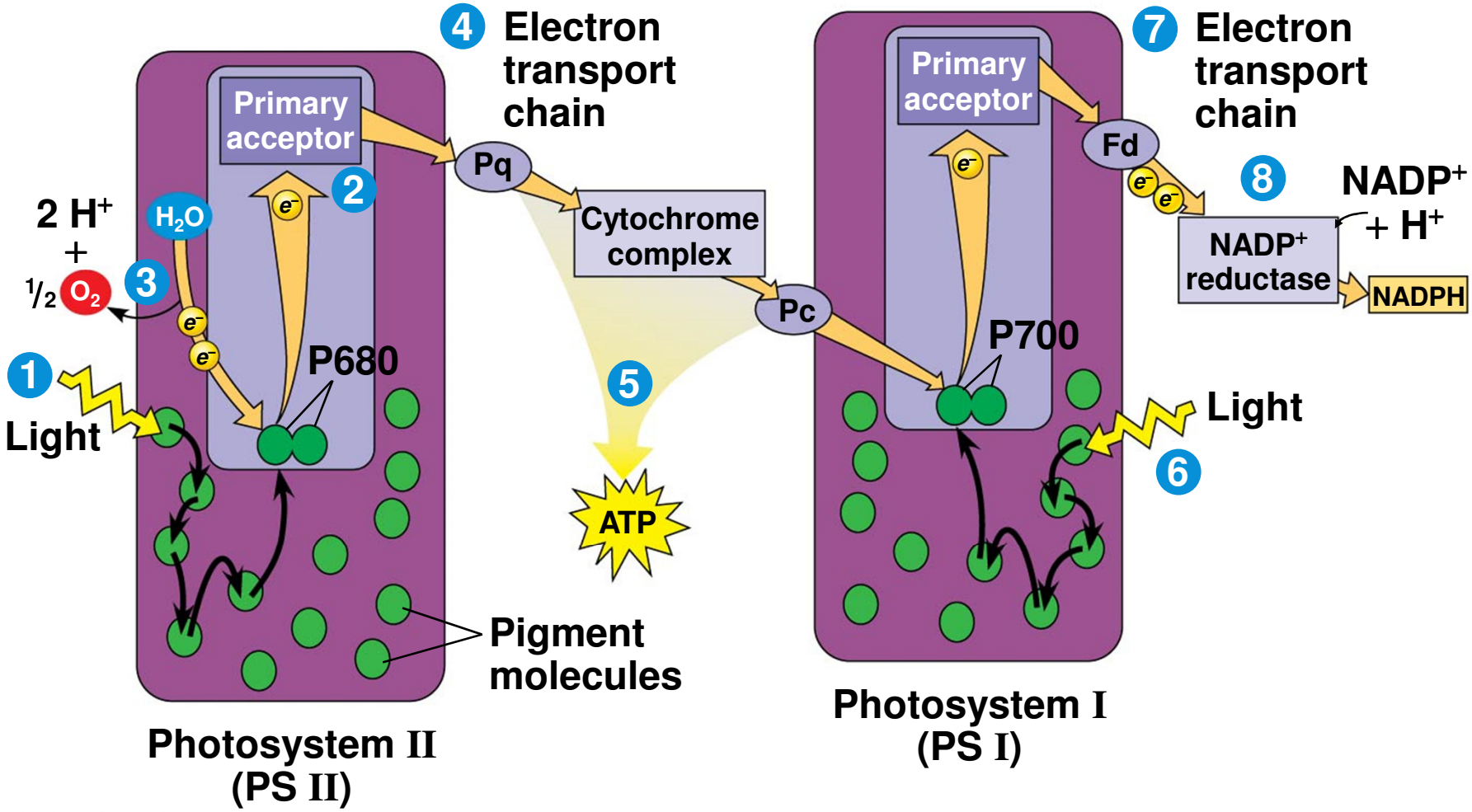
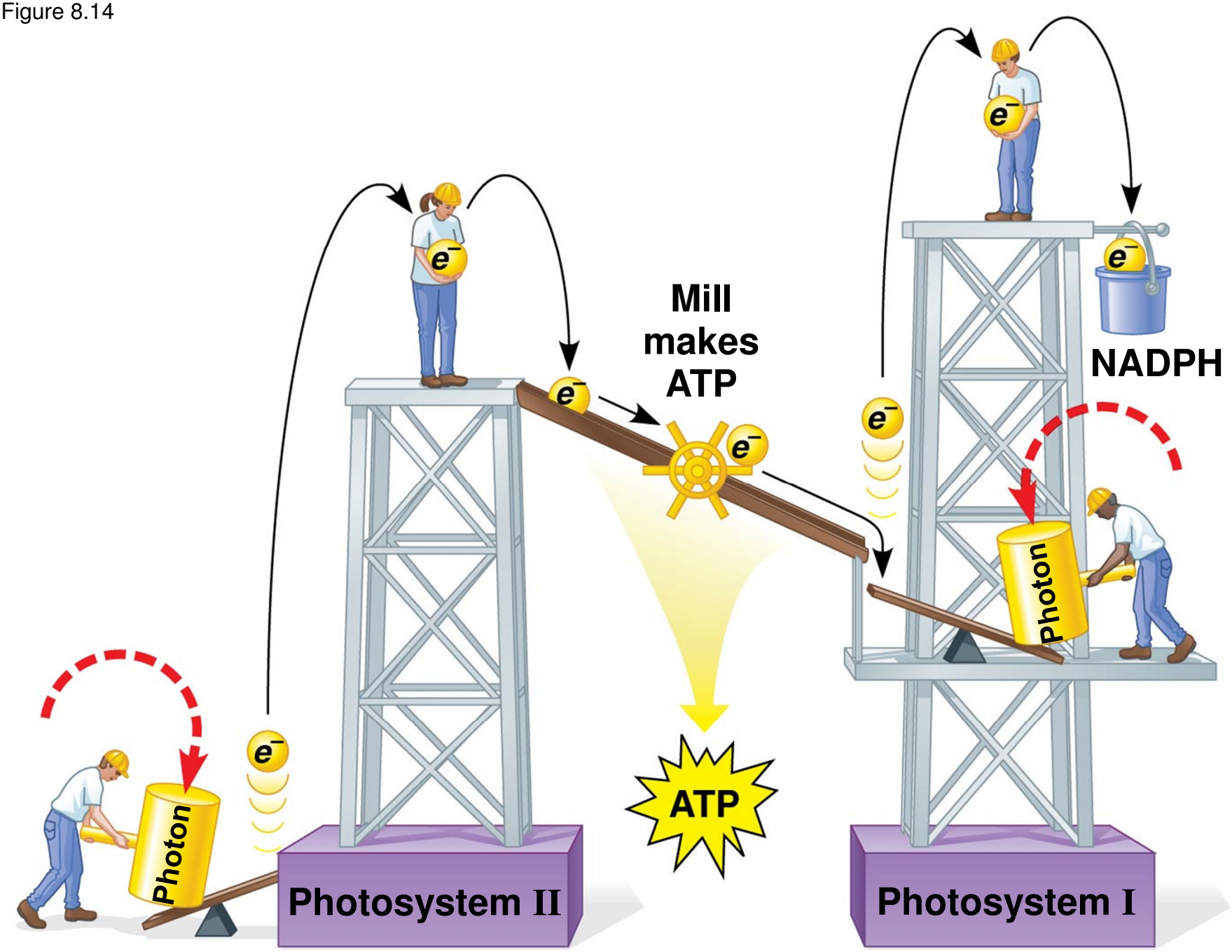

4 Electron transport chain
Primary acceptor
2
Pq
Cytochrome complex
Pc
2 H+
+
1/2 O2
H2O
3
e−
e−
P680
1
Light
5
ATP
Pigment molecules
Photosystem II
(PS II)
Primary acceptor
P700
Fd
7 Electron transport chain
8
NADP+
+ H+
NADP+ reductase
NADPH
Light
6
Photosystem I
(PS I)

Figure 8.14

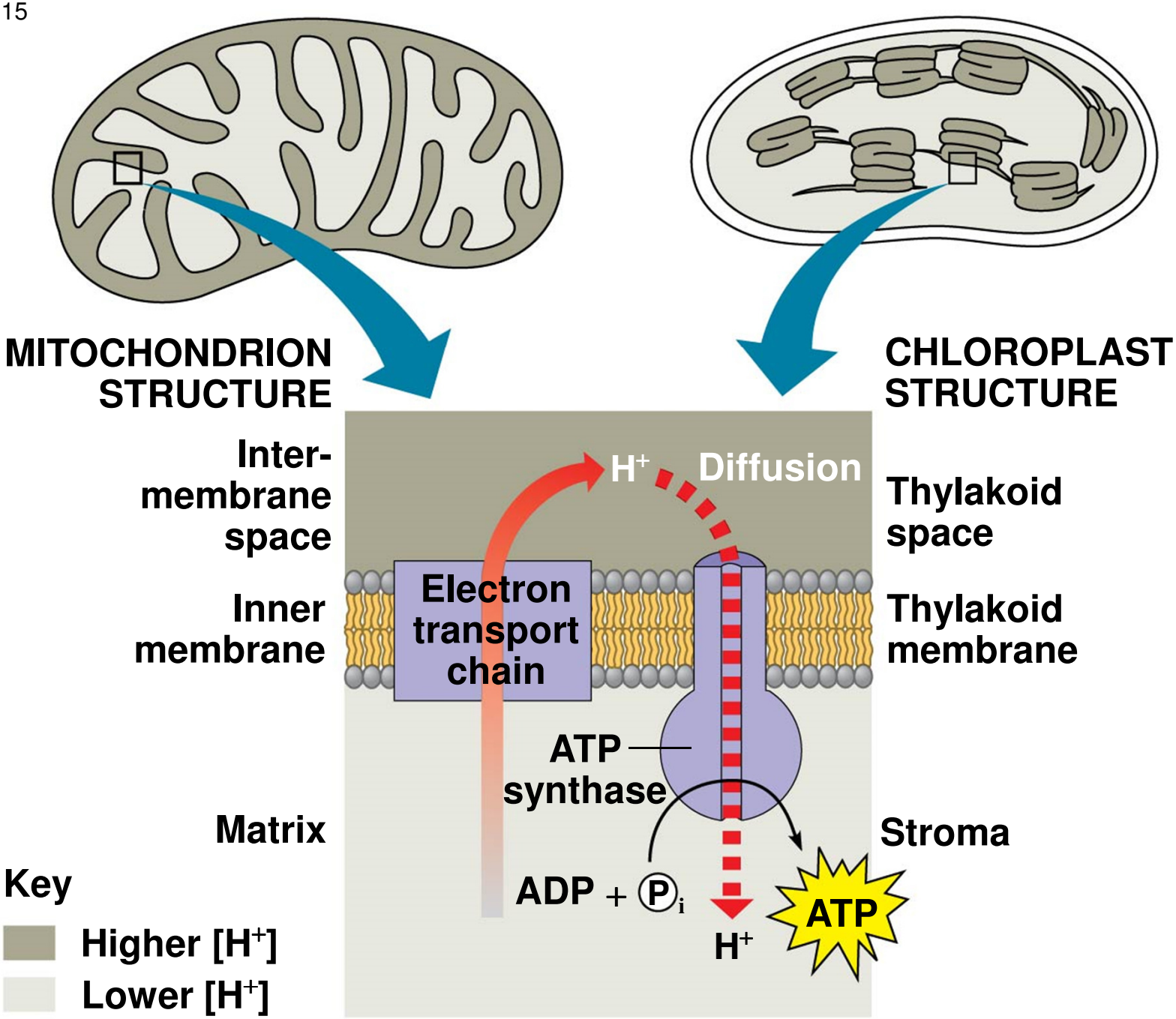

Mill makes ATP
NADPH
Photon
Photon
ATP
Photosystem II
Photosystem I

A Comparison of Chemiosmosis in Chloroplasts and Mitochondria

- Chloroplasts and mitochondria both generate ATP by chemiosmosis but use different sources of energy
  - Mitochondria transfer chemical energy from food to ATP
  - Chloroplasts transform light energy into the chemical energy of ATP

- Spatial organization of chemiosmosis differs between chloroplasts and mitochondria but also shows similarities
  - Thylakoid space and intermembrane space are comparable
  - Mitochondrial matrix is analogous to stroma of chloroplast
- In mitochondria, protons are pumped to the intermembrane space and drive ATP synthesis as they diffuse back into the mitochondrial matrix
- In chloroplasts, protons are pumped into the thylakoid space and drive ATP synthesis as they diffuse back into the stroma

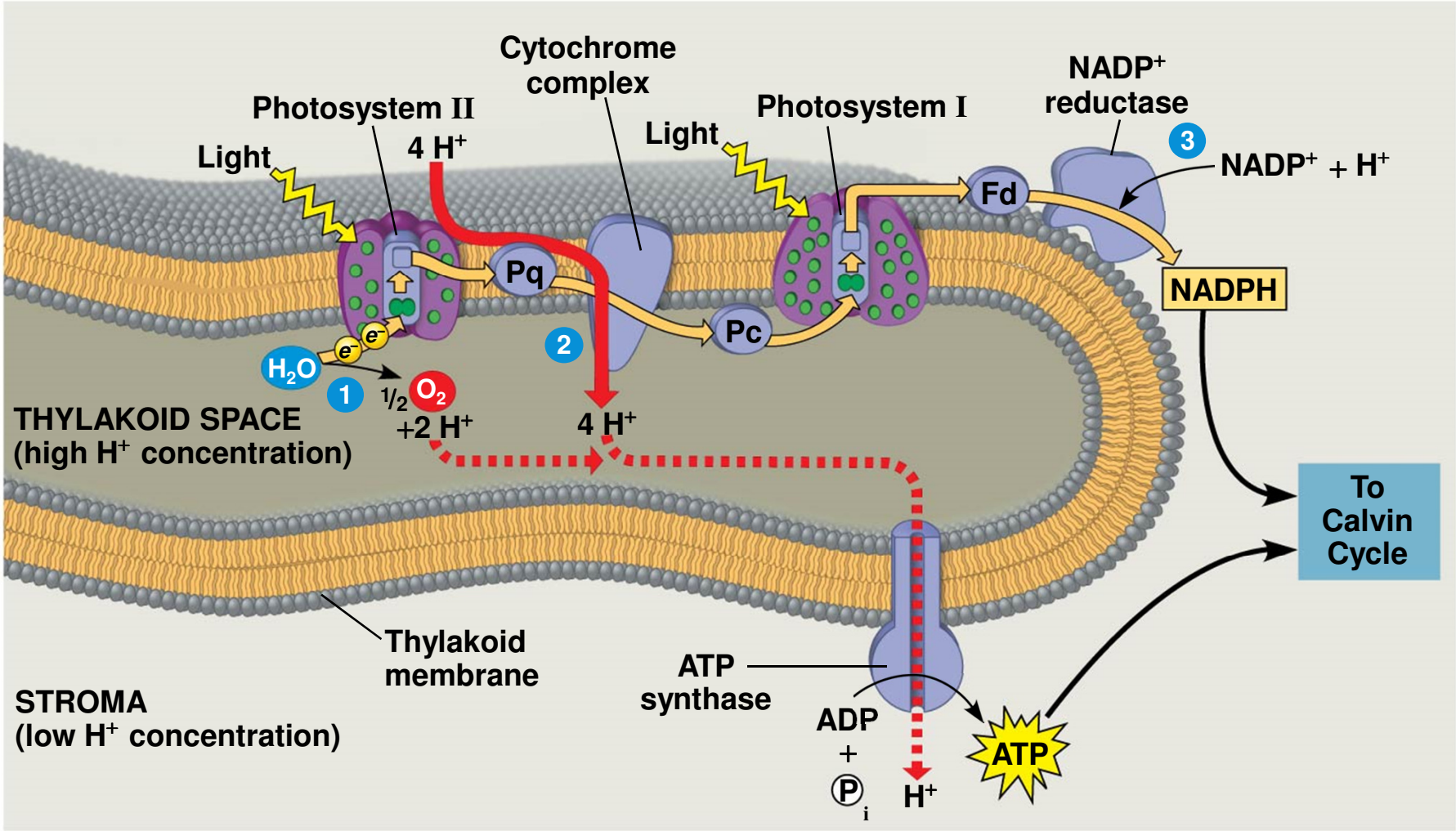
Figure 8.15


MITOCHONDRION STRUCTURE
CHLOROPLAST STRUCTURE
Inter-membrane space
Inner membrane
Matrix
Thylakoid space
Thylakoid membrane
Stroma
H+
Diffusion
Electron transport chain
ATP synthase
ADP + Pi
ATP
H+
Key
Higher [H+]
Lower [H+]

- ATP and NADPH are produced on the side facing the stroma, where the Calvin cycle takes place

- In summary, light reactions generate ATP and increase the potential energy of electrons by moving them from H_2O to NADPH
  - Oxygen is a by-product

Figure 8.16


Cytochrome complex
Photosystem II
Light
4 H+
Light
Photosystem I
NADP+ reductase
3
NADP+ + H+
Fd
Pq
Pc
NADPH
2
e−
e−
H2O
1
1/2 O2
+2 H+
4 H+
THYLAKOID SPACE
(high H+ concentration)
To Calvin Cycle
Thylakoid membrane
ATP synthase
ADP + Pi
H+
ATP
STROMA
(low H+ concentration)

Concept 8.3: The Calvin cycle uses the chemical energy of ATP and NADPH to reduce CO_2 to sugar

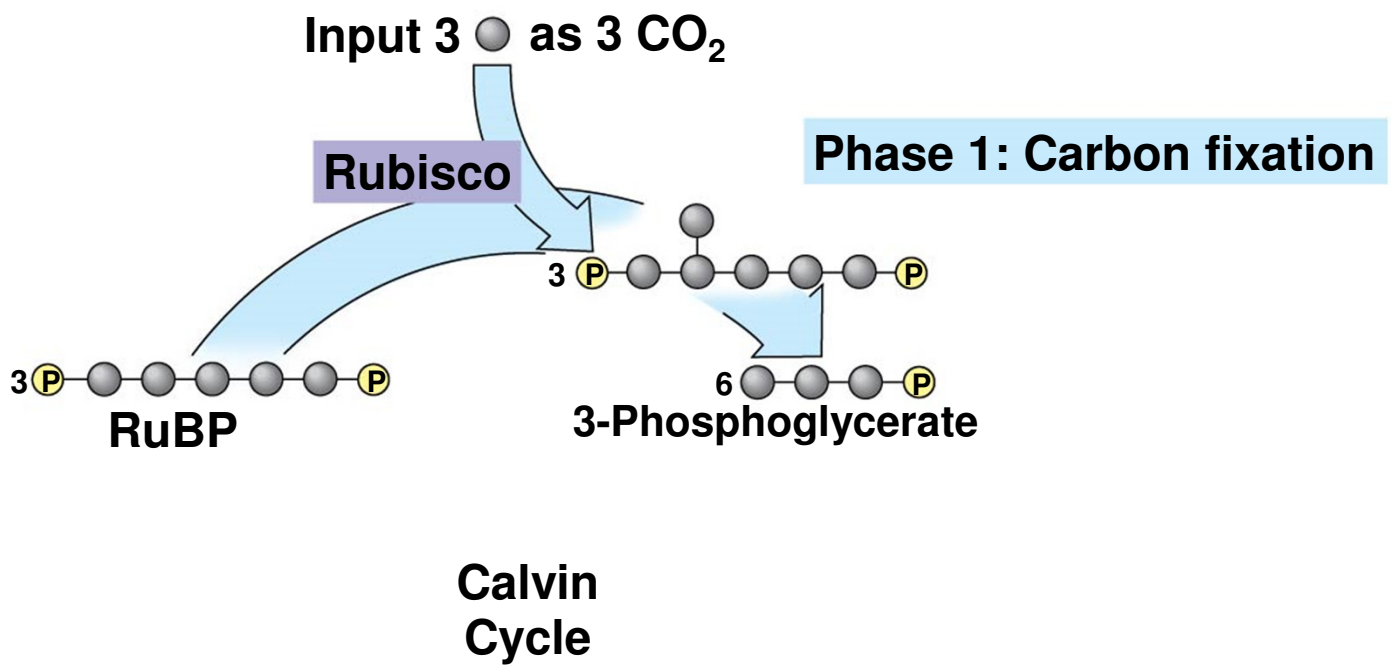
- The Calvin cycle, like the citric acid cycle, regenerates its starting material after molecules enter and leave the cycle
- Unlike the citric acid cycle, the Calvin cycle is anabolic
  - It builds sugar from smaller molecules
  - Consumes energy by using ATP and the reducing power of electrons carried by NADPH

- Carbon enters the cycle as CO_2 and leaves as a sugar named **glyceraldehyde 3-phospate (G3P)**
- For net synthesis of one G3P, the cycle must take place three times, fixing three molecules of CO_2
- The Calvin cycle has three phases
  - Carbon fixation
  - Reduction
  - Regeneration of the CO_2 acceptor

- **Phase 1**, **carbon fixation**, involves the incorporation of the CO_2 molecules into ribulose bisphosphate (RuBP) using the enzyme **rubisco**
- **Phase 2**, **reduction**, involves the reduction and phosphorylation of 3-phosphoglycerate to G3P
  - One molecules exits cycle to be used by plant cell
  - Other five must be recycled to rengerate RuBP
- **Phase 3**, **regeneration**, involves the rearrangement of G3P to regenerate the initial CO_2 receptor, RuBP

- For the net synthesis of one G3P molecule, the Calvin cycle consumes 9 ATP and 6 NADPH

Figure 8.17-1



Calvin
Cycle

Figure 8.17-2

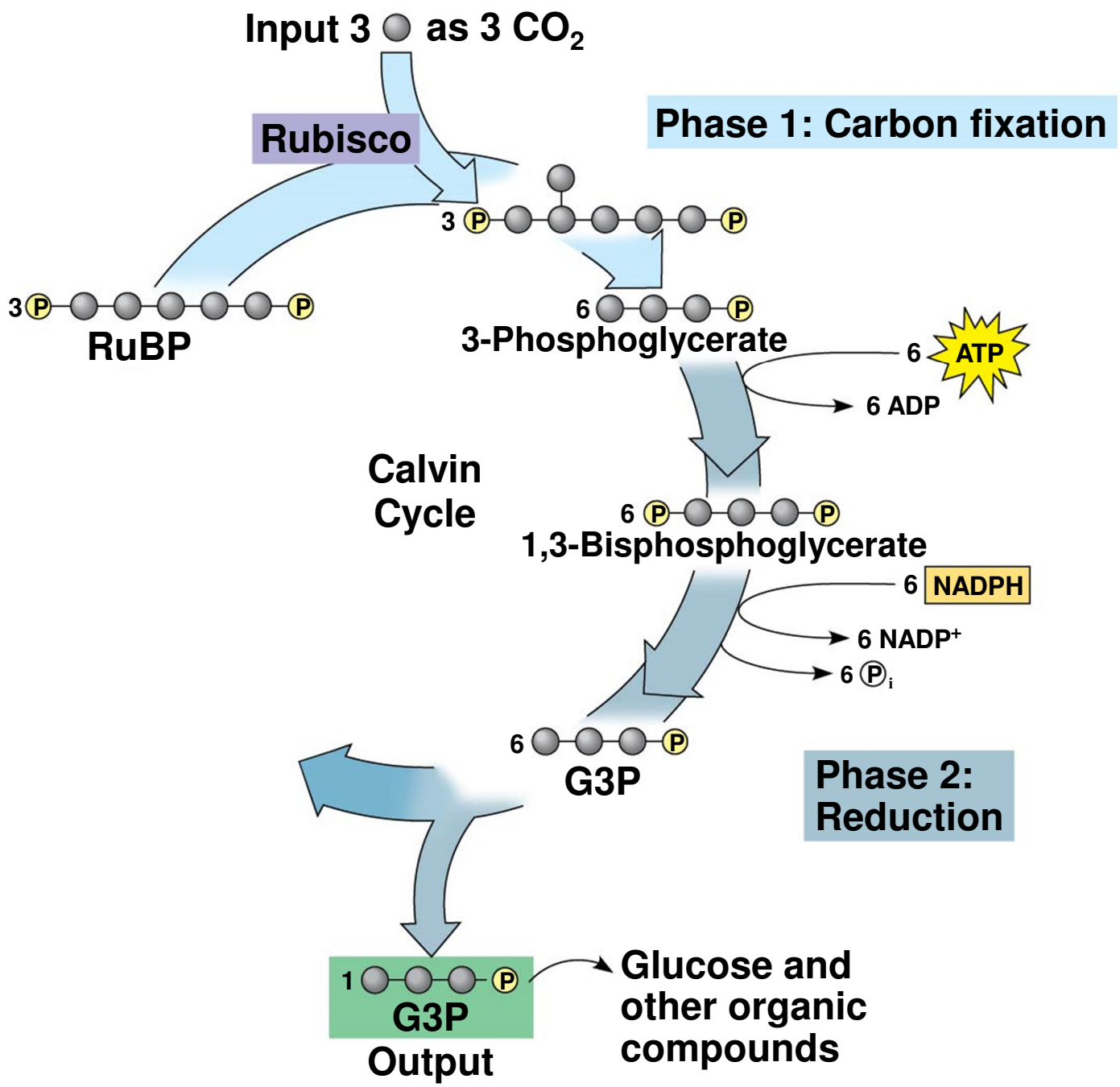
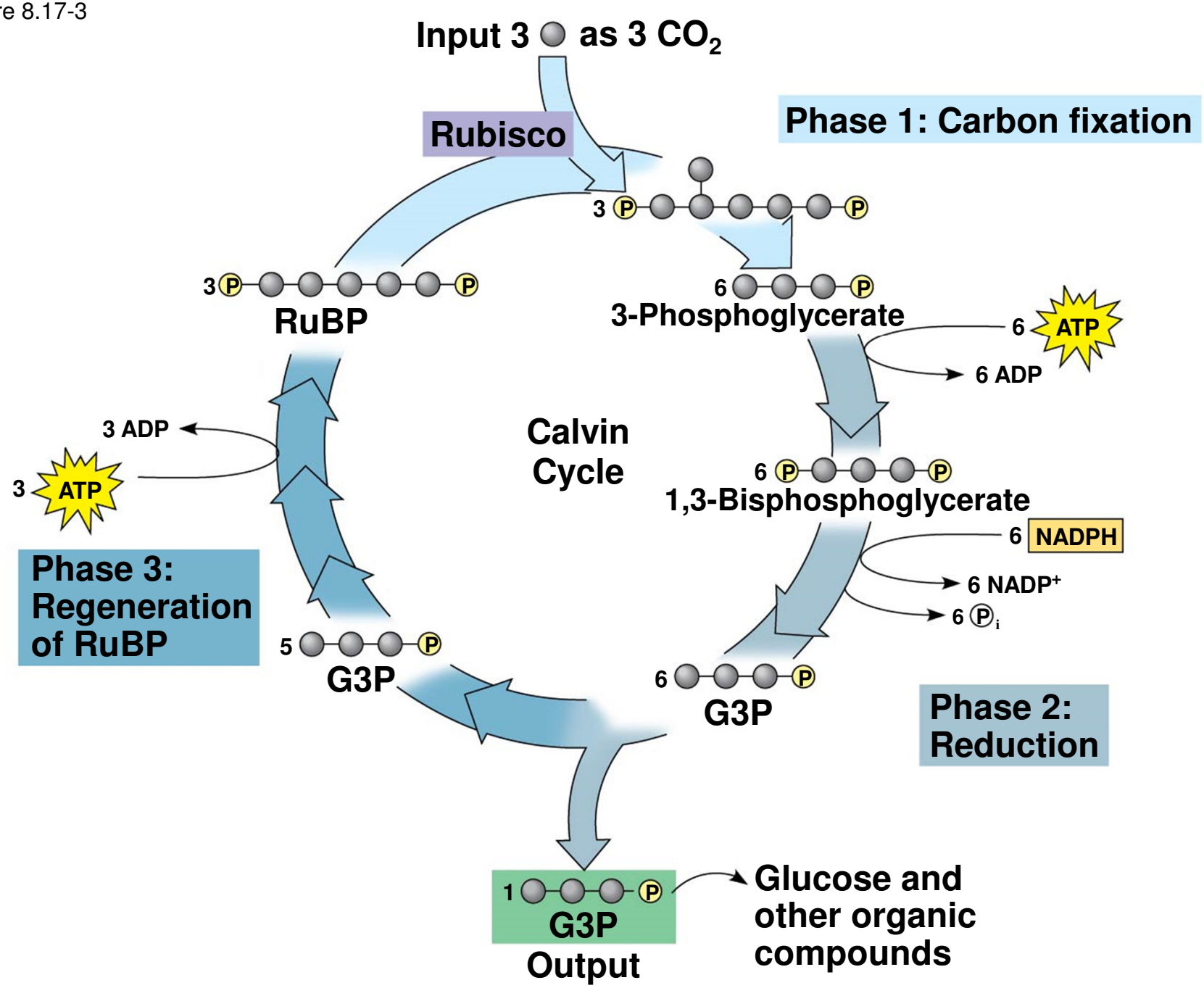

Input 3 as 3 CO_2
Rubisco
Phase 1: Carbon fixation
3 P P
3 P P
RuBP
6 P
3-Phosphoglycerate
6 ATP
6 ADP
Calvin Cycle
6 P P
1,3-Bisphosphoglycerate
6 NADPH
6 $NADP^+$
6 P_i
6 P
G3P
Phase 2: Reduction
1 P
G3P
Output
Glucose and other organic compounds

Figure 8.17-3


Input 3 as 3 CO_2
Rubisco
Phase 1: Carbon fixation
3
P
P
3
P
P
RuBP
6
P
3-Phosphoglycerate
6
ATP
6 ADP
3 ADP
3
ATP
Calvin Cycle
6
P
P
1,3-Bisphosphoglycerate
6
NADPH
6 $NADP^+$
6 P_i
Phase 3: Regeneration of RuBP
5
P
G3P
6
P
G3P
Phase 2: Reduction
1
P
G3P
Output
Glucose and other organic compounds

Evolution of Alternative Mechanisms of Carbon Fixation in Hot, Arid Climates

- Adaptation to dehydration is a problem for land plants, sometimes requiring trade-offs with other metabolic processes, especially photosynthesis
  - Stomata allows for exchange of gases but are also main avenues of evaporative loss of water
- On hot, dry days, plants close stomata, which conserves H_2O but also limits photosynthesis
- The closing of stomata reduces access to CO_2 and causes O_2 to build up
  - These conditions favor an apparently wasteful process called *photorespiration*

- In most plants (**C_3 plants**), the first organic product of carbon fixation, via rubisco, is a three-carbon compound
  - When they close their stomata on dry, hot days, C_3 plants produce less sugar
- C_3 plants include rice, wheat, and soybeans

- In **photorespiration**, rubisco adds O_2 instead of CO_2 in the Calvin cycle, producing a two-carbon compound
  - Uses ATP rather than generating it
  - Produces no sugar
  - But may provide protection against damaging products of light reactions that build up in the absence of the Calvin cycle

C_4 Plants

- **C_4 plants** minimize the cost of photorespiration by incorporating CO_2 into a four-carbon compound
  - Partially close stomata on hot/dry days to conserve water
  - But sugar continues to be made through function of 2 different types of photosynthetic cells
    - Mesophyll cells
    - Bundle-sheath cells
  - Spatial separation of steps
- C_4 plants include sugarcane and corn

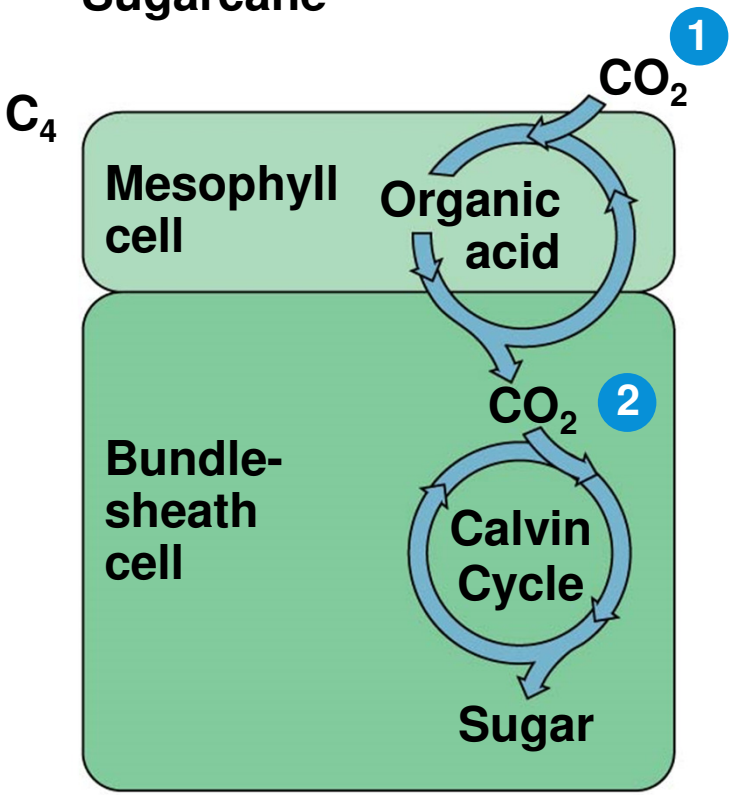
CAM Plants

- Some plants, including succulents, use **crassulacean acid metabolism (CAM)** to fix carbon
- **CAM plants** open their stomata at night, incorporating CO_2 into organic acids
  - Store in vacuoles until morning
- Stomata close during the day, and CO_2 is released from organic acids and used in the Calvin cycle
  - Light reactions can supply ATP and NADPH
- Temporal separation of steps
- CAM plants include pineapples and many cacti

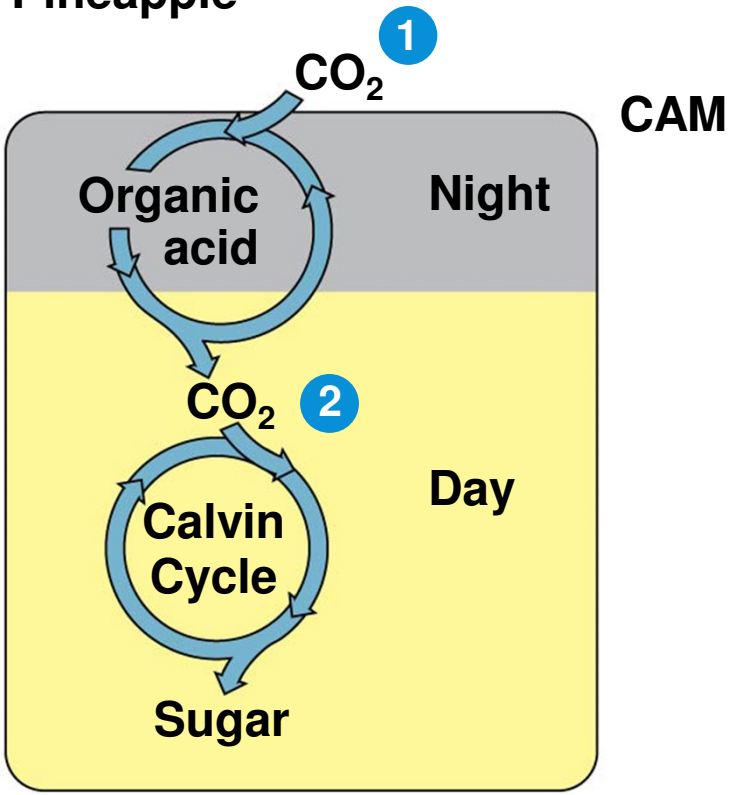
Figure 8.18

Sugarcane

Pineapple



(a) Spatial separation of steps



(b) Temporal separation of steps

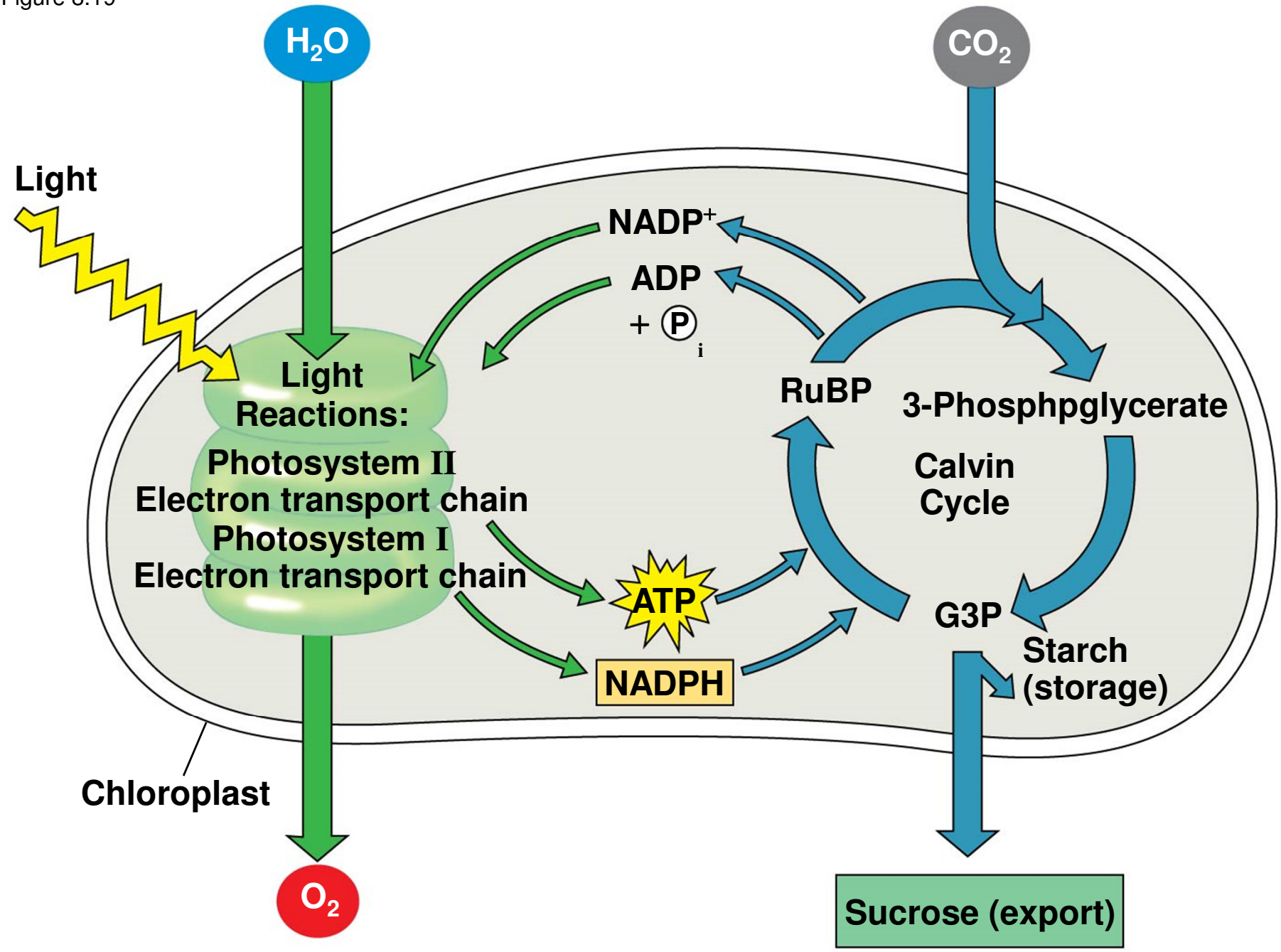
The Importance of Photosynthesis: *A Review*

- The energy entering chloroplasts as sunlight gets stored as chemical energy in organic compounds
- Sugar made in the chloroplasts supplies chemical energy and carbon skeletons to synthesize the organic molecules of cells
  - Some is consumed as fuel for cellular respiration in mitochondria of plant cells
  - Some is used to make cellulose
    - Main ingredient of cell walls

The Importance of Photosynthesis: *A Review*

- Plants store excess sugar as starch in the chloroplasts and in structures such as roots, tubers, seeds, and fruits
- In addition to food production, photosynthesis produces the O_2 in our atmosphere
- No process is more important to the welfare of life on Earth than photosynthesis!

Figure 8.19


H_2O
CO_2
Light
$NADP^+$
ADP
+ Ⓟ$_i$
Light
Reactions:
Photosystem II
Electron transport chain
Photosystem I
Electron transport chain
RuBP
3-Phosphpglycerate
Calvin
Cycle
ATP
NADPH
G3P
Starch
(storage)
Chloroplast
O_2
Sucrose (export)

- Light reactions
  - Occur in thylakoid membranes
  - Convert light energy to chemical energy of ATP and NADPH
  - Split H_2O and release O_2 to atmosphere
- Calvin Cycle reactions
  - Take place in stroma
  - Use ATP and NADPH to convert CO_2 to the sugar G3P
  - Return ADP and $NADP^+$ to light reactions